COSMIC RAY STARS IN PHOTOGRAPHIC EMULSION AT HIGH ALTITUDE

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ABSTRACT. Ilford G_5 photographic plates were sent in jet planes to an altitude of 7100 m and stars formed in the emulsion were investigated. 70.5% of the stars are found to be produced by neutrons; the size distribution of stars formed by charged and neutral primaries are represented in two histograms. The ratio of α-particles to protons released in a star is studied as a function of star size and this ratio is found to be constant at 0.43 for stars with 8 or more prongs. Energy distribution of α-particles from stars, as well as the variation of the number of grey particles with star size are presented graphically; mean energy of α-particles is found to be 13.4 Mev and the number of grey tracks is seen to increase linearly with star size. The size number distribution of all stars has been studied and this seems to be represented by two straight lines: $N(>n) = A \exp(-0.341n)$ for $n \leqslant 6$, and $N(>n) = B \exp(-0.256\,n)$ for $n > 6$. The distribution curve is compared with those obtained by other workers at 3460 m and 21000 m respectively and a steepening of slope with decrease of altitude is noted. A method of obtaining energy spectrum from the size distribution is indicated.

INTRODUCTION

The first experimental evidence for the nuclear disintegrations caused by cosmic rays in photographic emulsion is due to Blau and Wambacher (1937). They obtained pictures of sets of tracks radiating from a common origin, which came to be known as "stars". Such a star was caused by the simultaneous ejection of several ionizing particles from a disintegrating nucleus. These stars were subsequently investigated with improved types of emulsions by various workers like Perkins (1947, 1950), Lord and Schein (1949), Yagoda *et al.* (1949), George and Jason (1949), Camerini *et al.* (1949), Brown *et al.* (1949), Bernardini *et al.* (1950) and Page (1950).

Most of the previous observations were carried out at mountain altitudes. The present experiment was however undertaken to study the phenomenon of star formation in photographic emulsion at altitudes higher than that of mountain stations, in order to investigate their size distribution, the relative number of charged and neutral primaries among the star producing radiation and also some special features regarding the nature of secondaries from stars.

EXPERIMENTAL DETAILS

Sealed containers with Ilford G_5 plates, 100μ thick, were sent up in military jet aircrafts flying on short trips at an average altitude of 7100 m, the total exposure time for each packet at this altitude being about 10 hours.

The tracks emanating from the stars were divided into three categories according to their grain densities, g :

(1) "Thin" tracks, $g < 1.5g_{min}$,

(2) "Grey" tracks, $1.5g_{min} < g < 5g_{min}$

(3) "Black" tracks, $g > 5g_{min}$,

where g_{min} is the grain density of a relativistic and singly charged particle.

The grey and black tracks have been classified together as "heavy" tracks. In case of protons, black tracks correspond to particles of energy less than about 40 Mev; grey tracks of energy between 40 and 330 Mev, and thin tracks of energy greater than about 330 Mev. A star size is usually expressed by the number of prongs emanating from the star.

Photomicrographs of a few typical stars recorded in the present experiment are shown in Fig. 1.

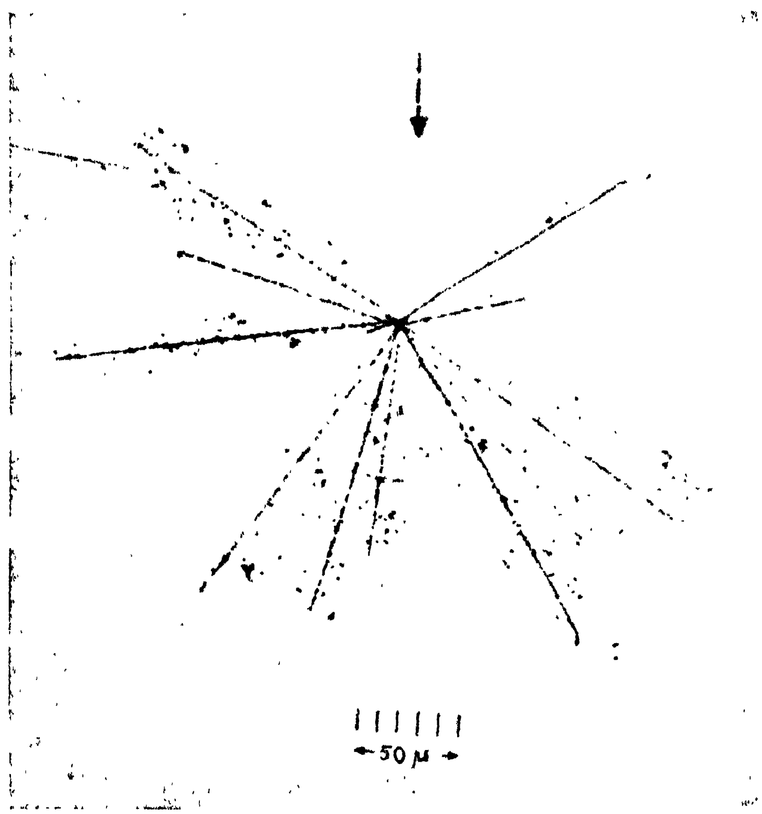

Fig. 1 (a) A star induced by a neutral particle. The probable direction of incidence of the primary is indicated roughly by the arrow.

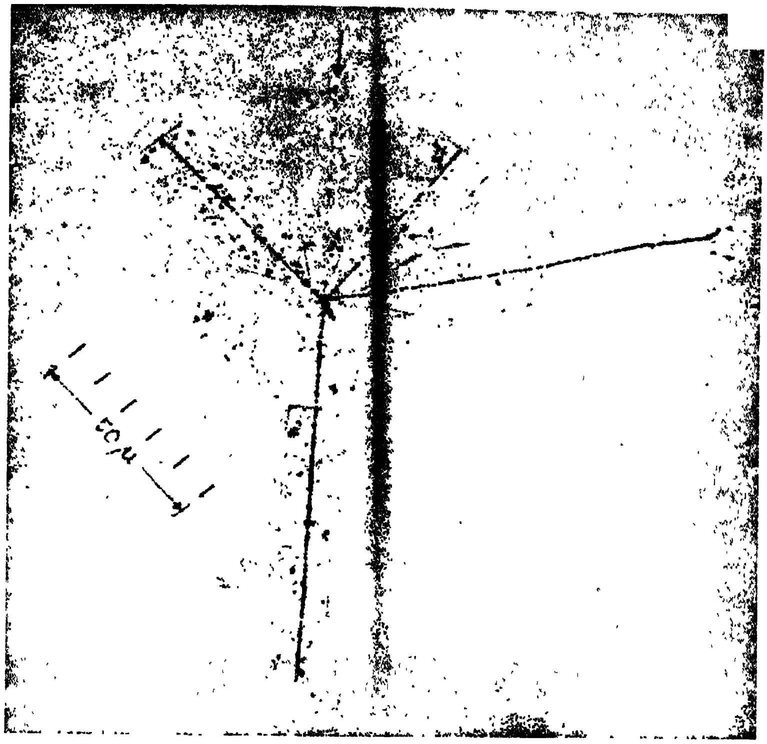

Fig. 1(b) A star induced by a charged particle. The path of the primary particle is indicated by the arrow.

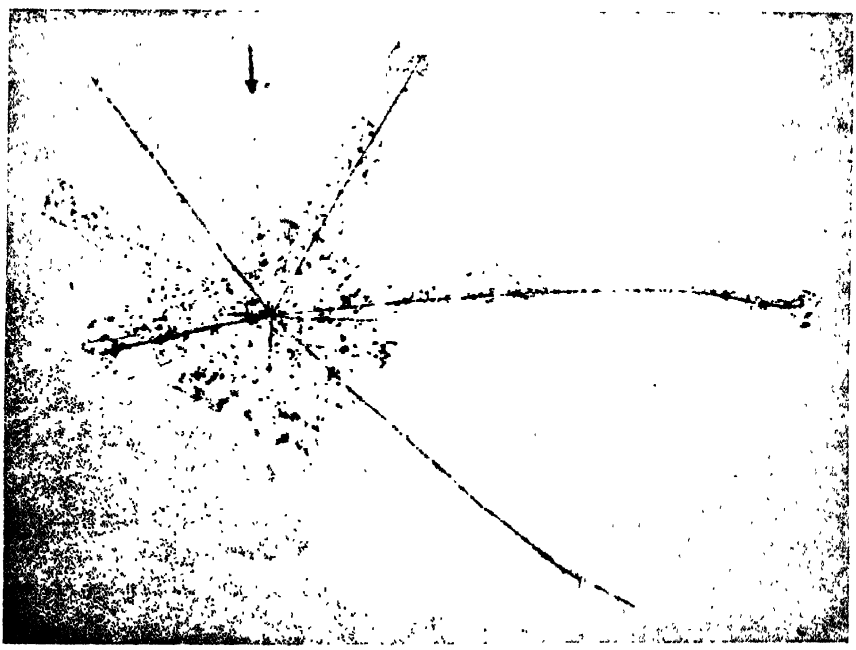

Fig. 1(c) A star induced by a charged particle. The arrow indicates the path of the primary particle.

RESULTS AND DISCUSSIONS

A. *Nature of the primaries producing stars*

During the exposure, the plates were kept in a definite orientation with the emulsion side lying in a vertical plane, the same end of the plate always facing upwards. It was thus possible to determine the direction of motion of a particle during its passage through the emulsion, relative to the vertical. It was observed that most of the thin tracks were inclined at small angles to the vertical. It was therefore reasonable to assume that most of the thin tracks "above" (i.e. in the upper hemisphere) the stars were due to initiating particles, whereas the thin tracks in the lower hemisphere were due to secondaries.

A second criterion for distinguishing the primary of a star was obtained from the following considerations. The disintegration of a heavy nucleus following the collision of a high energy particle proceeds in two separate steps. The first is the ejection from the nucleus of mesons and of high energy nucleons; the second is the "evaporation" of the residual excited nucleus. The first type of emitted particles produces thin tracks which are well collimated around the initial direction of motion of the primary, whereas the evaporation tracks do have almost isotropic distribution. The primary nucleon will, therefore, lie on the axis of symmetry of the emitted thin tracks and on the other hemisphere of the star.

Whenever a thin track was observed in the upper hemisphere of a star at a small angle with the vertical, and/or more or less in line with the axis of symmetry of the secondary fast particles, then that particular star was recognised as being produced by a charged primary; the absence of such a track would designate the star as being induced by a neutral primary. The primary particles, if charged, are mostly protons while the uncharged ones are usually neutrons. Somewhat similar discrimination was adopted by Brown *et al.* (1949) and Page (1950) to identify the primary of a star. Some of the stars, however, could not be recognised with regard to their primaries and they were left out of the following analysis.

(i) *Relative multiplicity of stars due to charged and uncharged primaries*

Stars were analysed according to whether they were induced by charged or uncharged primaries and it was found that 70.5% of the total number of stars recorded had been initiated by neutral particles.

This may be compared with the relative rate at 3460 m altitude as measured by Page (1950) and by Brown *et al.* (1949). These results are listed in Table I together with the results of the present investigation.

If it is assumed that the cross-section for star production is the same for charged (protons) and uncharged (neutrons) primary particles, the above results show that at the atmospheric depths considered, neutrons capable of producing stars are more numerous than the protons.

TABLE I

Author	Altitude	Percentage of stars formed by Charged primaries	Neutral primaries
1. Page	3460 m	17.0	83.0
2. Brown *et al.*	,,	17.4	82.6
3. Present authors	7100 m	29.5	70.5

Most of the particles responsible for the stars at these depths are of secondary origin and their abundance in the atmosphere is determined by their rate of production and their rate of decay. The rate of production of protons and neutrons in air is mostly the same, but while neutrons disappear only by nuclear collisions, protons lose energy by ionization also. Therefore a comparatively smaller number of protons will be able to reach the lower atmosphere from an upper layer where they are produced.

Also, the relative number of protons will be smaller, with greater atmospheric depth of observation. This is illustrated from the rates at different altitudes as shown in Table I.

(ii) *Size distribution of stars due to charged and neutral primaries*

The number of stars induced by charged and uncharged primary particles as a function of star size are represented by the histograms shown in Fig. 2(a) and 2(b). The histograms clearly point out the difference in the size distribution in the two cases. In case of stars with fewer prongs, the neutron induced stars are much more in number than those induced by protons; whereas in case of larger stars both are about equally numerous. The same results were also obtained by Page (1950).

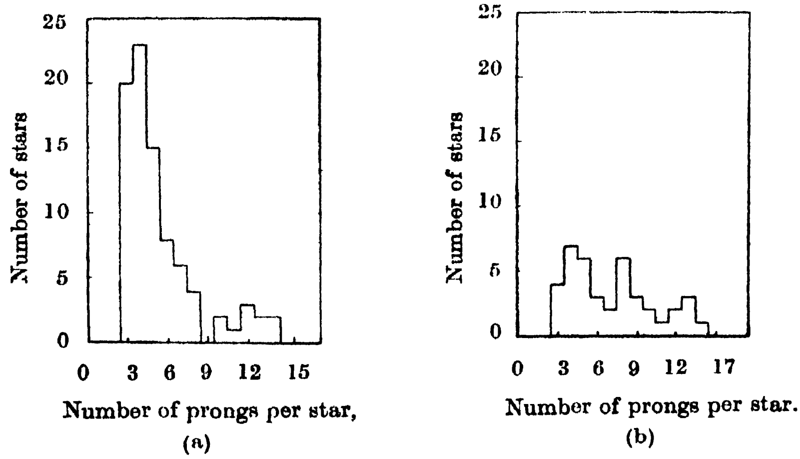

Fig. 2. Number of stars as a function of star size.
(a) Stars induced by charged primaries. (b) Stars induced by neutral primaries.

The difference in the frequency of stars formed by neutrons and protons can be explained as being due to their varied energy specturm. Compared to the neutrons, the protons are subject to an additional energy loss due to ionization. This effect becomes an important factor in the absorption of protons when the energy is sufficiently low. Thus at low energies there would be considerably more neutrons than protons, whereas at high energies, ionization loss is negligible and neutrons and protons will be present in comparable numbers. This explains why most of the low energy stars are neutron-induced.

B. *Some characteristics of the secondary particles emitted in a star*

In order to gain information regarding the process involved in the star formation, the measurements of some of the characteristics of the secondary particles were undertaken.

(i) *Alpha-proton emission ratio*

The low energy secondary particles emitted in a star are believed to be due to the "evaporation" process of the highly excited nucleus struck by the incident particle. The "evaporation" theory of nuclear disintegration was applied to the low energy particles from stars in photographic emulsion by Bagge (1946) and by Harding *et al.* (1949) and was extended further by Le Couteur (1950), who calculated the energy distribution of evaporated particles and also obtained the probability for the emission of different types of particles in a star as a function of the excitation energy of the nucleus.

One of the conclusions of the evaporation theory that can be easily checked against the experimental results is the ratio of alpha particles to protons among the secondaries of a star. The results of measurement of the mean proportion of alpha-particles in a star, for stars of different prong numbers are shown in Fig. 3. For larger values of prong number, particles heavier than alpha-particles were found to be emitted quite often. This phenomenon was also observed by Perkins (1950) and these prongs were excluded from the data plotted.

TABLE II

Authors	alpha to proton ratio
Perkins (1950)	0.50
Bernardini *et al.* (1950)	0.35
Page (1950)	0.37
Present authors	0.43

It is seen from Fig. 3 that the proportion of alpha-particles in a star decreases with increasing star size and for stars with greater than 8 prongs, the decrease is so slow that the ratio R of alpha-particles to the total number of heavy prongs may be taken to be a constant at a value of $R = 0.30$. This datum gives for alpha-particles to proton ratio as 0.43 (taking all the singly charged secondaries to be protons).

The values for the average ratio of alpha-particles to protons emitted in larger stars obtained experimentally by different workers are shown in Table II. The results of calculations (using parameter 'd') of Le Couteur (1950) on the basis of evaporation theory are also plotted in dotted line in Fig. 3 for comparison. It

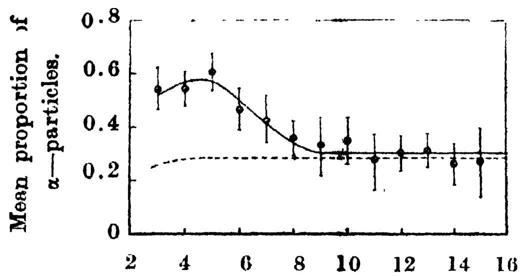

Fig. 3. Ratio of the number of alpha-particles to the total number of heavy prongs as a function of star size.

The dotted curve shows that calculated by Le Couteur (using his parameter 'd').

is seen that the calculated value of R is almost constant and equal to 0.28 and there is rough agreement between the theory and the present experimental results for larger stars.

The discrepancy for stars with small prong numbers are due to the stars formed in light C, O, N nuclei present in the emulsion, while Le Couteur's calculations refer to stars formed in Ag and Br nuclei. From the measurement of stars formed in pure gelatine, Perkins (1949) had shown that the alpha-proton ratio was much higher in stars formed in gelatine than in ordinary emulsion. It was also found that light C, N, O nuclei in emulsion contributed appreciably only to stars of less than about 6 to 8 prongs. This is also evident from the clear break at about prong number six in the size distribution curve of stars discussed later (in section C) in this paper. The above considerations explain the high value of alpha/proton ratio in smaller stars.

(ii) *Energy distribution of alpha-particles from stars*

The majority of alpha-particles emitted in stars stopped in emulsion. It was therefore possible to determine the distribution in energy of the alpha-particles by range measurement. The number of alpha-particles as a function of energy is represented in a histogram in Fig. 4 for stars with 6 or more heavy prongs (upto 15 prongs, which is the highest measured), only these stars being recognised as solely due to Ag and Br nuclei.

It is seen from Fig. 4 that the most probable energy of the α-particles is about 10 Mev while the average energy is 13.4 Mev. The general features of the distribution is in agreement to the measurements of other workers viz. Harding *et al.* (1949) and Perkins (1950).

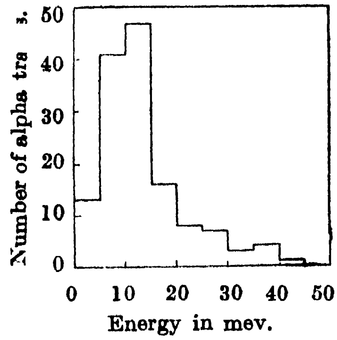

Fig. 4. Energy distribution of alpha particles from stars.

(iii) *Proportion of grey tracks*

Grey tracks are mostly due to protons of energy between about 40 Mev to 330 Mev and carry away most of the energy released in a star process. The average number of grey tracks was measured for stars with different number of heavy prongs and the results are shown graphically in Fig. 5. In order to reduce

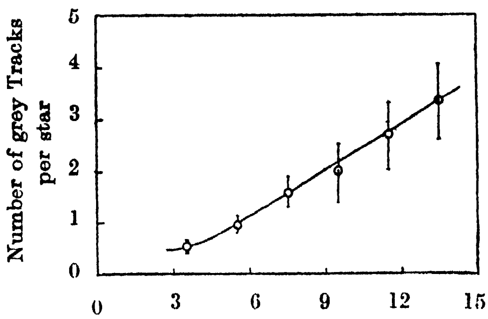

Fig. 5. Average number of grey tracks as a function of star size.

statistical errors, the star sizes have been grouped in twos, that is, grey tracks corresponding to stars of 3 and 4 prongs have been added together to give a single point in the graph, grey tracks from stars of 5 and 6 prongs are added to give the second experimental point, and so on.

It is seen from Fig. 5 that for the stars of 6 or more prongs, the number of grey tracks increases linearly with star size. The result is similar to that of Brown *et al.* (1949).

C. *Integral size distribution of stars*

The relative rate of occurrence of stars having different number of heavy prongs is represented in a semi-logarithmic plot in Fig. 6. In the present experiment, measurements were made only on stars having three or more prongs.

From the figure it is seen that the number (N) of stars decreases almost exponentially as the number (n) of heavy prongs per star increases. The experimental points, however, fall on two different straight lines in the semi-logarithmic plot, and the distribution can be expressed as :

$$N(>n) = A \exp(-0.341\, n) \text{ for } n \leqslant 6$$

and

$$N(>n) = B \exp(-0.256\, n) \text{ for } n>6, \tag{1}$$

where $N(>n)$ represents the number of stars having more than n heavy prongs, and, A and B are constants.

Page (1950) and George and Jason (1949) also reported similar distribution in the number of stars with star size, represented by two straight lines with different slopes. The clear break at approximately $n = 6$ arises due to the fact that the light nuclei C, N, O in emulsion do not contribute appreciably to stars of more than six prongs. This fact had been verified by Perkins (1949) by making measurements with alternate layers of pure gelatine and normal emulsion as mentioned earlier. Thus the stars with more than six prongs can be recognised as almost solely due to Ag and Br. nuclei and these stars fall on a separate single straight line in Fig. 6.

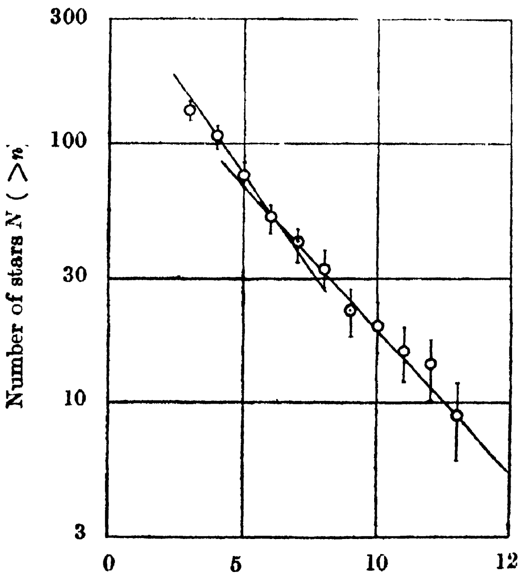

Fig. 6. Integral size distribution of stars.

When this size-number distribution found in the present experiment is compared with those obtained by other workers at different elevations, it is found that slope of the distribution curve changes with altitude, being steeper at lower elevations. To bring out this altitude variation of the power of the exponential distribution curve, integral size distribution of stars at three different elevations has been shown together in Fig. 7. Curve A is taken from that obtained by Page (1950) at 3460m, curve *B* is that of the present experiment (at 7100m) re-plotted from Fig. 6 while curve *C* is computed from the data of Camerini *et al* (1949) obtained at 21000m, the three (smoothed) curves being normalised at $n = 14$. The decrease in slope with increasing altitude is clearly distinguishable. This result may be explained from the fact that the average energy of the star producing

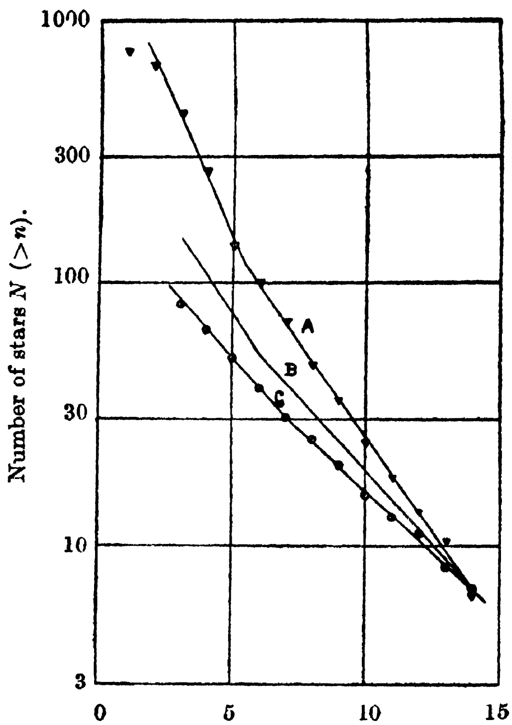

Fig. 7. Comparison of size distribution at different altitudes.
A—at 3460 m, obtained by Page (1950),
B—at 7100 m, present experiment,
C—at 21,000 m, obtained by Camerini *et al.* (1949).

radiation increases with elevation so that there are relatively more higher energy particles at upper elevation producing comparatively larger number of bigger stars.

The number of heavy prongs in a star is a measure of the energy of the initiating primary. The excitation energy of the evaporating Ag and Br nuclei disintegrating into slow particles (<30 Mev) had been calculated by Le Couteur (1950) and was found to be a linear function of the nuber of black prongs per star. But if the total energy, including also those released in thin and grey tracks, is considered, the energy of the primary is no more a linear function of the star size.

Brown *et al.* (1949) have made extensive measurements of the energy of the different types of particles emanating from a star and have shown that the primary energy can be expressed as a function of the star size by an empirical relation :

$$E = 37n+4n^2 \qquad \ldots \quad (2)$$

where n is the number of heavy prongs in a star. Assuming the cross-section for star production to be independent of the energy within the limits concerned, the size distribution of stars given by relations (1) at the atmospheric depth of 420g cm^{-2}, combined with an energy-size relation like that of equation (2), would give the energy spectrum of the star producing radiation (N-component of cosmic rays) at this depth.

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